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Coordinated Power Control Strategy based on Primary-Frequency-Signaling for Islanded Microgrids

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Abstract— In a flexible microgrid, the power regulation of each electronic-converter-based unit should be not only determined by the load demand, but also controlled according to the power and energy available in each unit. This paper proposes a coordinated control strategy in which each unit can operate in different operation modes taking into account the resource limitation. Firstly, a Primary-Frequency-Signaling (PFS) is introduced to realize coordinated control between units in a distributed way. Then the whole control structure of system is described in detail, which includes innerloop control with virtual impedance and primary control based on droop method for modes changes. The four modes changes for operation of ESS and RES are illustrated. Finally, simulation results will be presented to demonstrate and validate the proposed control strategy.

I. INTRODUCTION

Due to environmental concerns and fast development of power electronic technology, microgrids is becoming a very promising approach to deliver power in a distributed way compared to the conventional centralized power system [1].

With proper control strategies, microgrid can be operated in either grid-connected mode or islanded mode with seamless transformation [2]. In an islanded microgrid, energy generation from sources and power consumption of loads should be balanced based on coordinated control among units. Generally, renewable energy sources (RES) take the responsibility to provide average power to the loads, and energy storage system (ESS) operates as an energy buffer to compensate the fluctuation of power sources to loads. Usually ESS operates in voltage control mode (VCM) to fix the bus voltage and frequency, and RES regulates its output power in power control mode (PCM). Many researches have been investigated previously regarding the advanced control strategies of RES operated in PCM, and ESS in VCM respectively to satisfy the load side demand [3-5]. However, a practical islanded system may suffer from the limitation of power generation or storage capability. These specific situations require the whole system operates in a flexible way of power control which takes into consideration of conditions like maximum power point tracking (MPPT) of

RES, and state of charge (SoC) of ESS. Few researches have been done for this coordination control among RES, ESS and loads according to power regulation capability of units.

The conventional way for the system management to achieve coordinated control is supervisory control with communication link [6-7]. This algorithm utilizes a higher level controller to manage the power flow of each unit using physical communication setup, which may increase cost and complexity for microgrids.

This paper adopted an interesting way of communication which using the information of AC bus for coordinated operation. In this way, the external communication can be removed since the coordination relies on the power bus. It needs to notice that bus signaling method can also be used in DC grid power management and has potential for loads shedding [8-9]. In this paper, the bus signaling concept is utilized with bus frequency deviation as primary frequency signaling (PFS) to enable system achieving source scheduling automatically. The PFS principle and implementation will be illustrated in Section III.

Since coordinated control based on PFS requires each unit has capability to regulate output frequency based on its source condition and output power, droop control is very suitable to implement with PFS. The fundamental droop method is utilizing output frequency and amplitude of voltage to control the active power P and Q [10]. To achieve PFS, this paper proposes a control strategy using droop method for modes changes during different operation scenarios. In this paper, the four modes of system operation based on seamless modes changing droop control is illustrated in Section IV. Finally, simulation results are presented in Section V to verify the proposed control strategy.

II. COORDINATED CONTROL OF A ISLANDED MICROGRID

Fig. 1 shows an islanded microgrid which mainly includes RES units, ESS unit and loads. In islanded mode, the RES units operate as power sources to supply the power of loads. Usually, to make the full use of renewable energy,

it is always trying to make the RES units operate under MPPT status to supply the loads. However, since the power drawn from RES units has intermittent nature, the ESS will be employed in the system to buffer the energy between the power sources and loads. That is, if the power from RES units is higher than the loads, the ESS is charging to store the extra power, and SoC of ESS will increase. And when the power produced by RES units cannot maintain the loads, the ESS will discharge, at the same time SoC will decrease. When the SoC of ESS is becoming too high, RES should decrease the output power from MPPT point. Therefore, the aim of coordinated control in microgrid is to balance the power between sources and loads, which taking into account of source status at the same time utilizing the renewable energy as much as possible. The coordinated control strategy of islanded microgrid proposed in this paper performs at three stages:

- ESS is not full of charge and RES operates at MPPT
- ESS is approaching full of charge and RES operates below MPPT
- ESS retreats from full of charge and RES restores MPPT

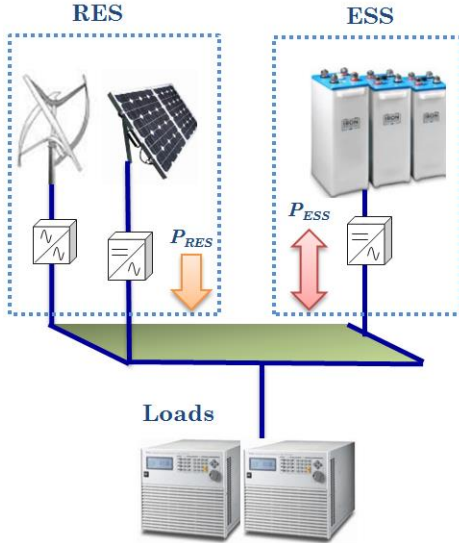


Figure 1. Description of islanded microgrids

III. PFS PRINCIPLE

The coordinated control of islanded microgrids can be achieved by using PFS method, which makes the coordinated control of RES and ESS units in primary level based on power electronic control technology. The coordinated operation is accomplished in a total distributed way without using any additional external communication link. To simplify the illustration, the explanation of the control strategy in the following section will be based on one ESS and one RES unit. Fig. 2 shows the control scheme of the system based on PFS method, where L and L_o are the filter inductance and output inductance, C is the output capacitor, v_c and i_L are capacitor voltage and inductor current used in

each unit for innerloop control output voltage regulation, i_o is output current which is used in droop control of primary level, SoC and MPPT are also taken into consideration of primary control for coordinated operation. It should be noticed that instead of using communication link, the control scheme uses the bus frequency information for the coordination. According to SoC status and output power of RES, the frequency will be changed slightly. And when the other unit senses the bus frequency reached the specific threshold, it will change mode to limit SoC or restore MPPT operation due to PFS.

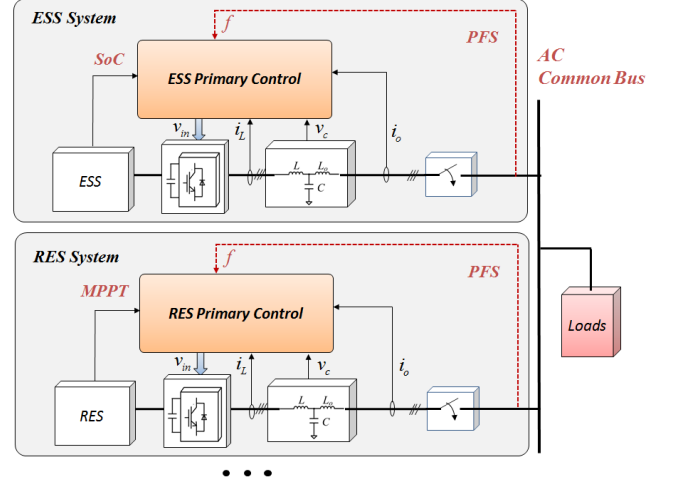


Figure 2. Control scheme of a microgrid based on PFS

In order to achieve PFS automatically, droop method is applied in the coordinated control strategy for the frequency regulation, which is described as

$$\begin{cases} \omega = \omega^* - k_{pP} \cdot (P - P^*) - k_{iP} \int_t (P - P^*) \\ E = E^* - k_{pQ} \cdot (Q - Q^*) - k_{iQ} \int_t (Q - Q^*) \end{cases} \quad (1)$$

where ω and E are the frequency and amplitude of the output voltages, ω^* and E^* are their references, P and Q are the output active and reactive power, and P^* and Q^* are their references. There are two modes of ESS and RES based on droop method: VCM and PCM, and they are applied for both ESS and RES systems in different situations. With only proportional term k_{pP} and k_{pQ} , the converter is controlled in VCM by the conventional proportional droop with constant slope. When activating integral term k_{iP} and k_{iQ} , the converter is controlled in PCM with infinite droop slope.

Fig. 3 shows the PFS principle applying this mode changes method when limiting the SoC of ESS. The system adopts the frequency thresholds to trigger the modes changes. At first, the RES is working in PCM based on MPPT with an infinite droop slope and ESS operates in VCM and they are stable at point A with ω_1 . Then ESS is becoming full of charge and changes its mode to PCM based on SoC signal. At this point, the droop slope of ESS is increasing and the bus frequency increases accordingly as the

system tends to provide more power than the loads can consume. In this period, both charging power of ESS and output power of RES will decrease. When the frequency reaches the threshold ω_2 and system operates at point B, the RES triggered to VCM by continuing to decrease the droop slope as a constant value. Finally, the whole system is stabilized at point C with ESS in PCM and RES in VCM. At this stage, the output power of ESS is controlled to zero with infinite slope.

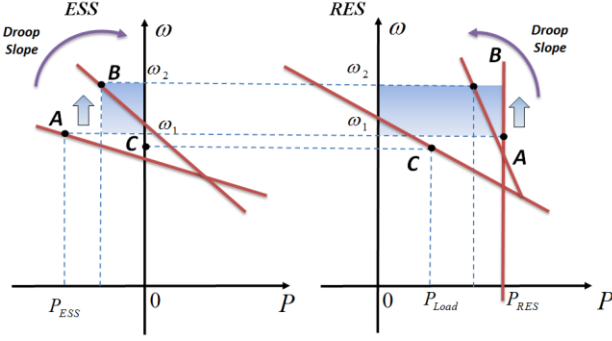


Figure 3. PFS principle when limiting the SoC of ESS

Fig. 4 shows the situation applying PFS principle when restoring MPPT operation of RES. At first, the system operates at point C when the system frequency is ω_3 , the RES is working in VCM to support loads and ESS is working in PCM with infinite slope to limit SoC. Then loads become heavier and the frequency of system is shifting downward results from the regulation of frequency of both ESS and RES. If the load is heavier compared to generation, the system frequency will decrease to the low threshold ω_4 and the system operates at point D. Then the ESS changes its mode to VCM and the slope is decreasing to a constant value, since it indicates that the RES cannot support the loads in VCM and ESS tends to discharge. At this stage, both ESS and RES are working in VCM mode to supply the loads. As the frequency decreasing, the power distributed by RES will increase. When it restores the MPPT point, the RES changes to the PCM with infinite slope and the whole system is stabilized at point E.

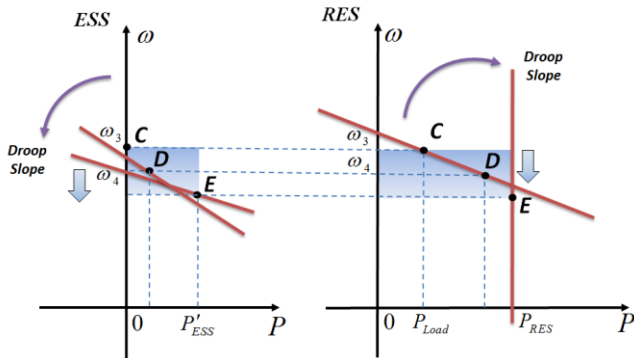


Figure 4. PFS principle when restoring MPPT of RES

IV. CONTROL STRATEGY IMPLEMENTATION

Since there are both VCM and PCM in ESS unit and RES unit, the control structure of the primary control for ESS and RES is unified, which can be divided into two parts: innerloop control with virtual impedance, and droop control with modes changes between VCM and PCM, the control structure is shown in Fig. 5.

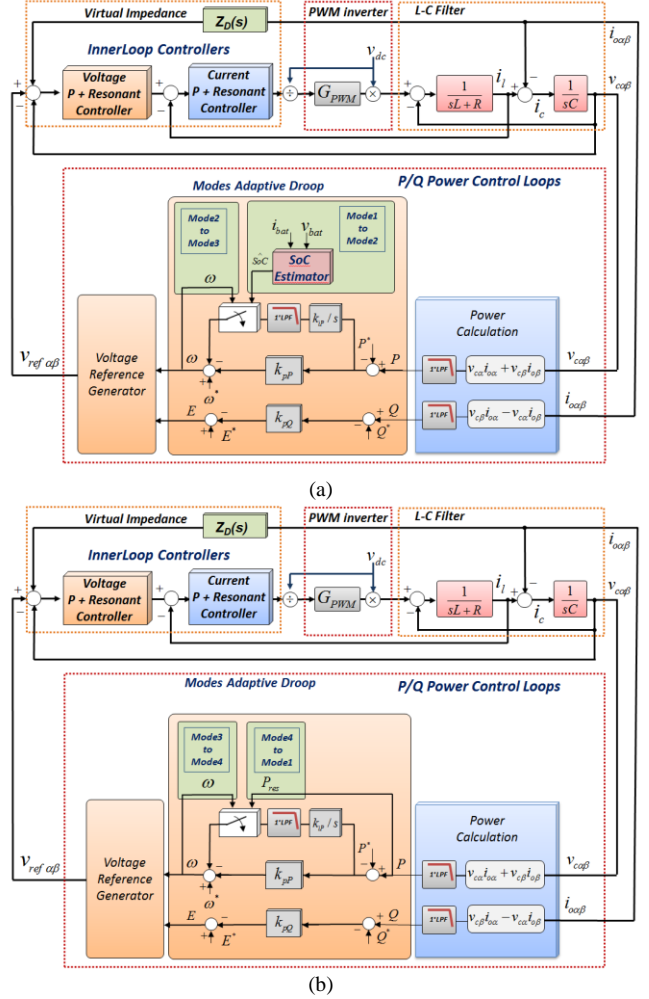


Figure 5. Control scheme of ESS (a) and RES (b) based on PFS

A. Innerloop Control with Virtual Impedance

The innerloop control is aiming at achieving good output capacitor voltage regulation. The three phase output voltages and filter inductance currents are controlled with proportional resonant (PR) controller, after transforming into $\alpha\beta$ reference frame. The innerloop controller is described as (2),

$$G_{in}(s) = k_p + k_{res} \frac{s}{s^2 + \omega^2} \quad (2)$$

where k_p and k_{res} are the proportional term and resonant term respectively, ω is the output angular frequency of the system.

The plant of LC filter can be written as,

$$G_p(s) = \frac{V_c(s)}{V_{in}(s)} = \frac{1}{LC \cdot s^2 + RC \cdot s + 1} \quad (3)$$

With the innerloop voltage control, the system transfer function can be written as,

$$V_c(s) = G_{cl}(s) \cdot V_{ref}(s) - Z_o(s) \cdot I_o(s) \quad (4)$$

In (4), $V_{ref}(s)$ is the output voltage reference, $G_{cl}(s)$ and $Z_o(s)$ are the close loop transfer function and output impedance respectively, which are defined as

$$G_{cl}(s) = \frac{G_i(s)G_u(s)G_{pwm}(s)}{[LCs^2 + (r + G_i(s)G_{pwm}(s))Cs + G_i(s)G_{pwm}(s)G_u(s) + 1]} \quad (5)$$

$$Z_o(s) = \frac{G_i(s)G_{pwm}(s) + Ls + r}{[LCs^2 + (r + G_i(s)G_{pwm}(s))Cs + G_i(s)G_{pwm}(s)G_u(s) + 1]} \quad (6)$$

where r is the parasitic resistance of filter inductance, $G_u(s)$ and $G_i(s)$ are the voltage controller and current controller in the form of (2) respectively, $G_{pwm}(s)$ is the transfer function of PWM module.

Based on P - ω and Q - V droop method, the output impedance is usually required as inductive. Therefore, virtual impedance is utilized to adjust output impedance as expressed in (7)

$$V_{ref}(s) = V_{ref}^*(s) - Z_v(s) \cdot I_o(s) \quad (7)$$

where $Z_v(s)$ is the virtual impedance, $V_{ref}^*(s)$ is the output voltage reference without virtual impedance. Then the adjusted output impedance is changed to (8)

$$Z'_o(s) = \frac{G_i(s)G_u(s)G_{pwm}(s)Z_v(s) + G_i(s) \cdot G_{pwm}(s) + Ls + r}{[LCs^2 + (r + G_i(s)G_{pwm}(s))Cs + G_i(s)G_u(s)G_{pwm}(s) + 1]} \quad (8)$$

The open loop plant and close loop transfer function of the system can be plotted as Fig. 6. And the output impedance Z_o with PR controller is shown in Fig. 7. It can be seen that with virtual impedance, the inductive behavior of the output impedance at fundamental frequency can be strengthened.

B. Droop Control with Modes Changes

With inductive output impedance, the active power and reactive power of each system can be controlled independently with output frequency and voltage using droop method as expressed in (1). Specifically, Q^* and k_{iQ} are set to be zero as the conventional droop, while for active power the integral term of droop is activated or not to make the unit change modes between PCM and VCM. Since both ESS and RES units have VCM and PCM modes, the

condition of adding or removing integral term of each unit is summarized in Table I. When k_{iP} on, the unit operates in PCM and while k_{iP} off, the unit operates in VCM. SoC_1 denotes the SoC limit of ESS, ω_{up} and ω_{down} are the up-threshold and down- threshold of system frequency, P_{MPPT} is the output power of RES at MPPT point.

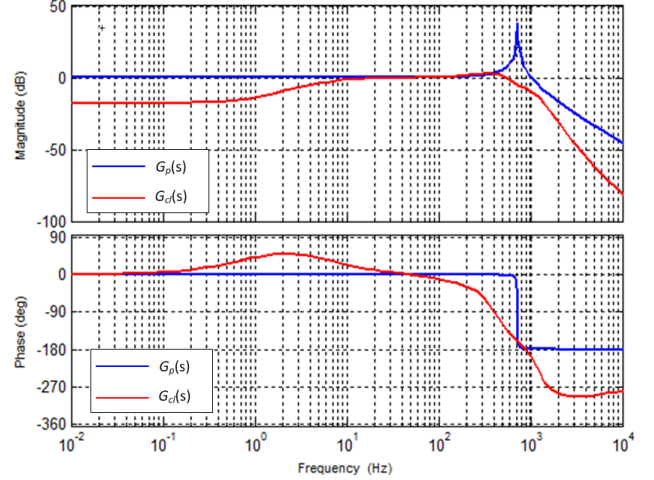


Figure 6. Bode diagram of $G_p(s)$ and $G_{cl}(s)$.

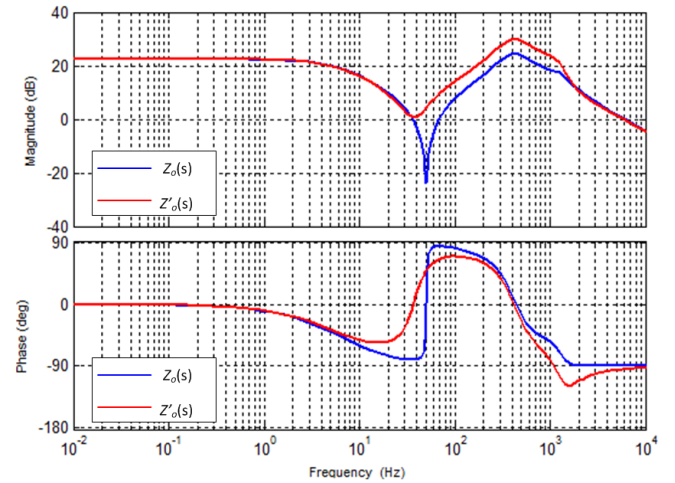


Figure 7. Bode diagram of $Z_o(s)$ and $Z'_o(s)$.

TABLE I. CONDITION OF MODES CHANGES

k_{iP}	ESS	RES
ON	$SoC > SoC_1$	$\omega \geq \omega_{up}$
OFF	$\omega \leq \omega_{down}$	$P = P_{MPPT}$

The modes changing process of ESS and RES is depicted as Fig. 8. Using the conditions of Table I, the ESS and RES change modes according to different situations as Table II shows.

V. SIMULATION RESULTS

To verify the proposed control strategy, simulation is carried out based on Matlab/simulink toolbox. The description of the power stage of the system is summarized in Table III. An islanded microgrid based on RES and ESS and local loads is simulated.

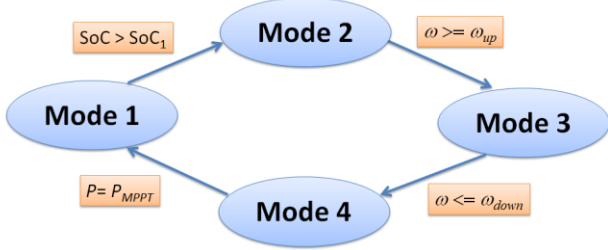


Figure 8. Modes changing process of ESS and RES

TABLE II. MODES DESCRIPTION

Mode	ESS	RES
1	VCM	PCM
2	PCM	PCM
3	PCM	VCM
4	VCM	VCM

TABLE III. DESCRIPTION OF POWER STAGE

Item	Symbol	Value
Nominal output voltage	V_o	230 V
Nominal output frequency	f^*	50 Hz
Filter inductor	L	1.8 mH
Output inductor	L_o	1.8 mH
Output capacitor	C	27 μ F

Fig. 9 shows the simulation results of the coordinated control system based on PFS. In the simulation results, the modes changes procedure among the four modes of both ESS and RES is presented. The different scenarios are described as following:

a. Before t_1 : The power of loads is 1.6kW, and the RES is operating under MPPT with output power of 2.5kW. The whole system is operating in Mode1.

b. t_1 - t_2 : SoC of ESS is above the up-threshold 85%, then ESS is changed to PCM and frequency begins to increase. The whole system is operating in Mode 2.

c. t_2 - t_3 : The bus frequency increases to the up-threshold, then RES is changed to VCM. The whole system is operating in Mode 3.

d. t_3 - t_4 : Loads change from 1.6kW to 2.7kW. The ESS starts to discharge and the frequency decreases.

e. t_4 - t_5 : The bus frequency decreases to the down-threshold, then ESS is changed to VCM. The whole system is operating in Mode 4.

f. t_5 - t_6 : The power of RES increases to the MPPT point, then RES is changed to PCM. The whole system is operating back to Mode 1.

g. After t_6 : The loads changes to 3.2kW. Since whole system operates in Mode1, ESS discharges more power to loads, and RES operates in PCM with MPPT.

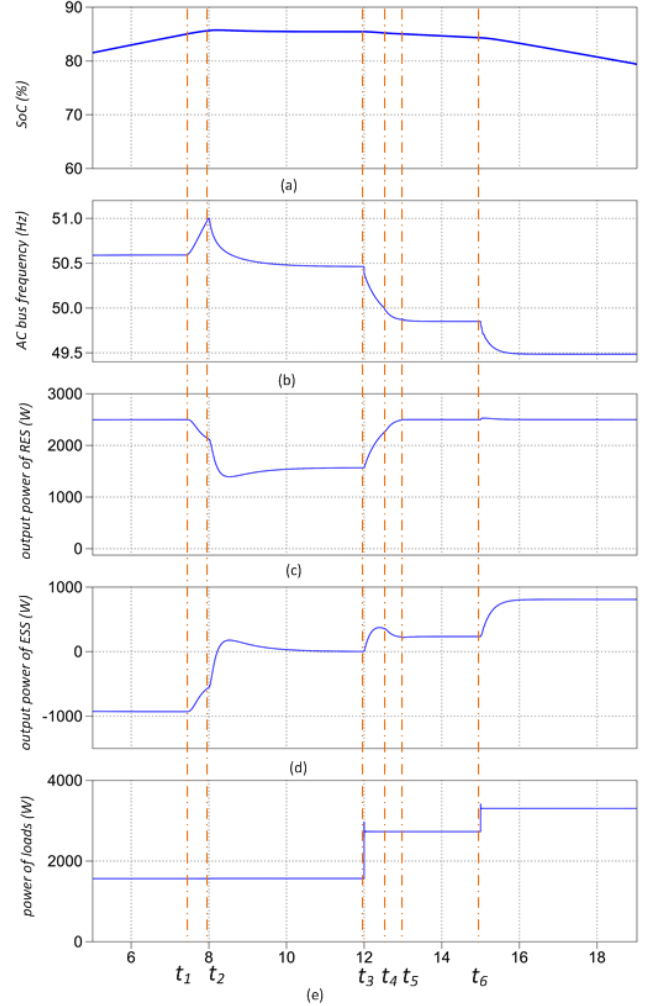


Figure 9. Simulation results of coordinated control based on PFS

VI. CONCLUSION

This paper presented a coordinated control strategy for islanded microgrids based on PFS. The aim is to coordinate ESS and RES unit to deal with the situation of source limitation. The PFS principle is introduced to achieve the coordinated control without communication link. Then control strategy based on droop method and virtual impedance is implemented. In the primary level, the PFS

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utilized four modes for the operation of ESS and RES, the modes changes procedure was illustrated. The simulation results were presented to show the verification of the proposed control strategy.

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